New HST Views at Old Stellar Systems

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Summary. HST has recently revealed that many among the most massive globular clusters harbor multiple stellar populations, and –most surprisingly– some of them are extremely helium rich. How these clusters managed to generate such complex stellar populations, and what processes let to so dramatic helium enrichment, is today one of the most exciting puzzles in the astrophysics of stellar systems. HST has also been instrumental in demonstrating that both the bulge of our own Galaxy and that of M31 are dominated by old stellar populations, coeval to galactic globular clusters. Ultradeep HST imaging has also demonstrated that a major component of the M31 halo is metal rich and much younger than old globular clusters.

1 Introduction

HST has enormously contributed to the study of old resolved stellar populations, in the Milky Way as well as in nearby galaxies. As this Conference is meant to celebrate the impact of HST on European astronomy, it is worth saying that European astronomers have often played a prime role in the achievements with HST in this field. This brief review will focus on the the most exciting HST results obtained by them in recent years, either leading the corresponding projects, or participating as co-investigators.

2 Helium-Rich populations in Globular Clusters

Globular clusters (GC) have always been prime targets for HST. Yet, a wealth of extremely exciting and unexpected results have been recently obtained with ACS, which partly contradict the long-standing view of these objects as prototypical *simple stellar populations* (SSP), i.e. assemblies of coeval stars all with the same chemical composition. Early results with HST indeed confirmed such a view, showing exquisitely narrow sequences in the color-magnitude diagram (CMD) of the best studied clusters. HST superior spatial resolution was instrumental in producing such CMDs, as it allowed superb photometric accuracy *and* proper-motion decontamination from foreground/background stars (e.g., for the cluster M4[1]). These early results reinforced the notion that sees GCs as viable SSP templates.

One exception to this paradigm was known since the early 'seventies, i.e. ω Centauri, whose broad RGB indicated that stars are distributed over a wide range of metallicities. This is emphatically illustrated by a recent CMD of ω Cen from a 3×3 ACS mosaic, shown in Fig. 1[2], with its multiple turnoffs, broad RGB, and complex HB morphology. Being the most massive GC in the Galaxy, ω Cen was not felt as a too embarrassing exception: thanks to its deeper potential well it may have retained enriched gas out of which successive stellar generation were formed. Perhaps, it also started much more massive than at present, possibly a compact dwarf galaxy in itself.

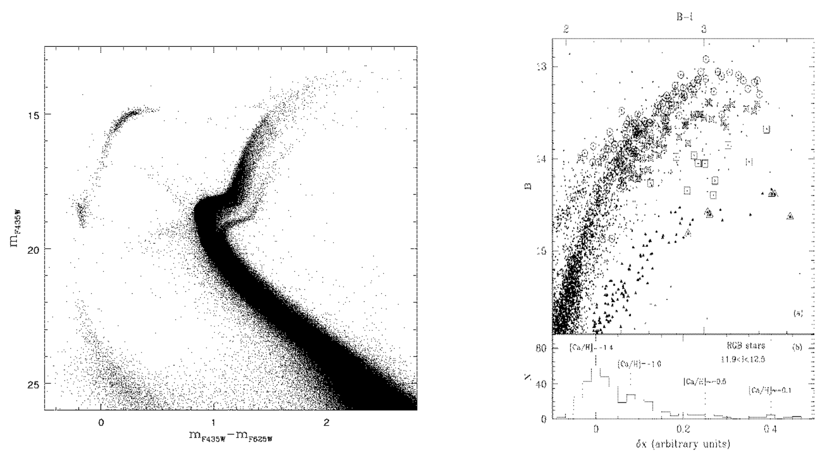

Fig. 1. Deep CMD of ω Cen from a 3×3 ACS mosaic[2] showing all the evolutionary phases from the main to the white dwarf sequence. The fine structure of the upper RGB is shown on the right panel, with the histogram giving the stellar distribution across a section of the RGB[3].

A first surprise came from a particularly accurate CMD of ω Cen obtained with WFPC2[4], shown here in Fig. 2. The main sequence (MS) appears in fact split in two parallel sequences, indicating that at least two distinct star formation episodes had to take place, rather than a continuous star formation process. A third distinct population is also evident in Fig. 1, from its faint turnoff and subgiant branch (SGB) and very red RGB. So, ω Cen harbors at least three distinct populations. Now, the majority of stars in this cluster are relatively metal poor, as indicated e.g., by the blue side of the RGB being the most populated (see Fig. 1). One would then expect that the least populated of the two MSs in Fig. 2 would correspond to the minority, metal rich population. However, Bedin et al.[4] noted that the metal rich MS should lie to the red of the metal poor one, instead it lies to the blue! This is just contrary to what well understood stellar models predict. Among the possible solutions of the conundrum Bedin et al. mention an enhanced helium

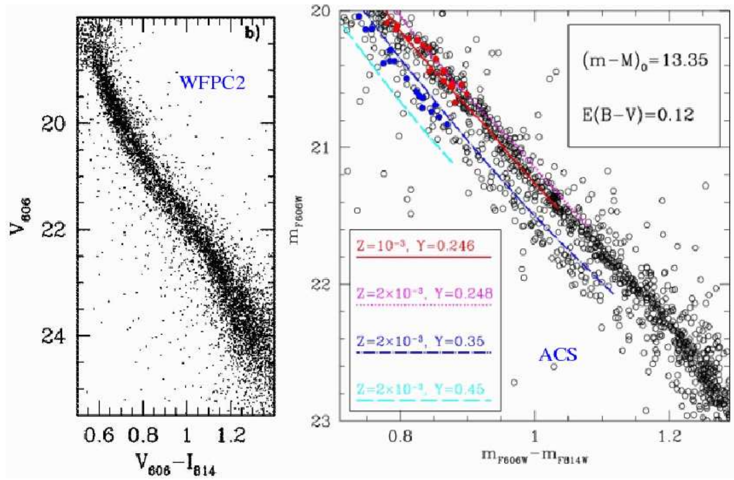

Fig. 2. Left panel: the main sequence of ω Cen splits in two parallel sequences in this CMD from WFPC2 data[4]. Right panel: the double main sequence of ω Cen is even better resolved using ACS data, with overlapped theoretical sequences with appropriate metallicities and different helium abundances[6].

abundance up to $Y \sim 0.3$ or more in the metal rich population, a solution further convincingly explored by Norris[5]. That the blue MS is indeed the metal rich one was then demonstrated spectroscopically using the FLAMES multiobject spectrograph at the VLT[6], and at this point it became virtually inescapable to conclude that the cluster contains a minority population with an helium abundance as high as $Y \simeq 0.35$.

Fig. 3 shows a blow up of the turnoff and SGB region of the CMD in Fig. 1. It is clear that at least four distinct populations coexist (labelled A, B, C, and D), and there is a rather convincing trace of a fifth one, intermediate between C and D. Indeed, a section of the RGB shows the presence of five populations, each with a different metallicity[7]. Thus, in ω Cen one can distinguish at least 3 MSs (the third being relative to the D population seen in Fig. 3), 4 or 5 SGBs, 5 RGBs, and a complex, multimodal HB. The real puzzle is how to connect the various parts of the CMD, recognizing each of the five MS-SGB-RGB-HB sequences, and estimate age, metallicity and helium (t, Z, Y) for each of the corresponding populations.

To help composing this puzzle, FLAMES spectroscopy at the VLT was then undertaken focusing on the SGB components[8][2]. The conclusions of these two studies differ somewhat, with one favoring nearly equal ages (within 1-2 Gyr uncertainty) for the five populations, but each with a distinct helium abundance[8], while the other argues for at least four age/metallicity groups with a $\sim$ 30% age range, having assumed just two helium abundances[2]. The t, Z, Y combinations of the five populations remain discrepant from one

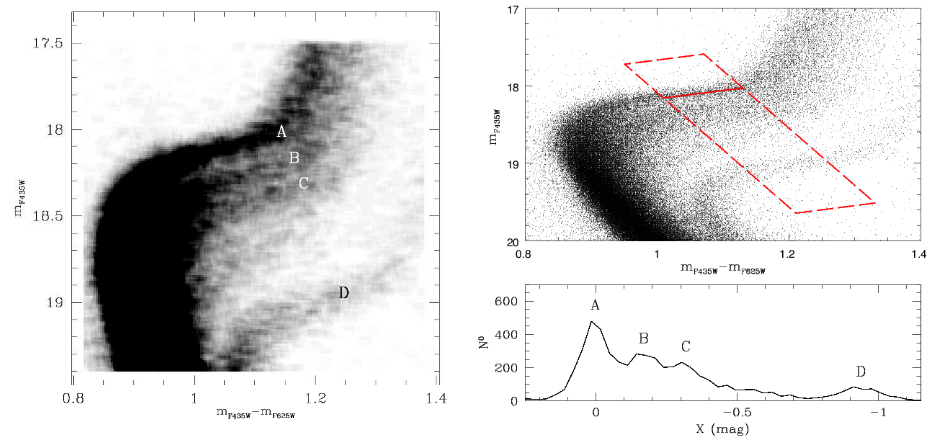

Fig. 3. Left: the Hess diagram of the turnoff/SGB portion of the ω Cen CMD in Fig. 1, showing 4 (perhaps) 5 distinct SGBs. Right: The same portion of the CMD with indicated the cut used for the number counts shown in the lower panel[2].

study to another (see also[9]), but only narrowing down these discrepancies one will understand the formation of such a complex cluster.

Whereas ω Cen had for a long time been regarded as a unique exception, suddenly it started to turn out that it was not at all so. Another cluster, NGC 2808 was known for having a multimodal HB, somehow analog to that of ω Cen[10]. Thus, it was speculated that the multimodal HB of this cluster could also be due to a multimodal distribution of helium abundances among the cluster stars[11]. Rarely speculations receive such a fine observational confirmation as was the case for this one: Fig. 4 shows the *triple* MS of this cluster, for which no metallicity differences appear to exist[12]. Thus, with 3 distinct MSs, 3 groups of RGB stars with different [O/Fe] ratios[13], and an HB made of 4 separated clumps, NGC 2808 hosts at least 3 distinct populations, each with different helium, from $Y \simeq 0.24$ up to $Y \simeq 0.37$.

For two other clusters, namely NGC 6388 and NGC 6441, helium-rich sub-populations have been suggested in order to account for their unique HB morphology and periods of the RR Lyrae variables[14][15]. At this point it soon became apparent that all 4 GCs with multiple, helium-enhanced populations were very massive, i.e. among the 11 GCs in the Galaxy which are more massive than $10^6 M_\odot$. Of the remaining most massive clusters, 47 Tuc does not show evidence for multiple populations, but NGC 1851 does (Piotto et al. in preparation). Among this set of supermassive globulars, NGC 6715 is being observed in Cycle 15 and NGC 6093, 6388, 7078, and 7089 will be observed in Cycle 16 (PI G. Piotto), in all cases aiming at checking whether there is evidence for multiple MSs. So, we shall soon know.

These exciting discoveries still ask more questions than give answers:

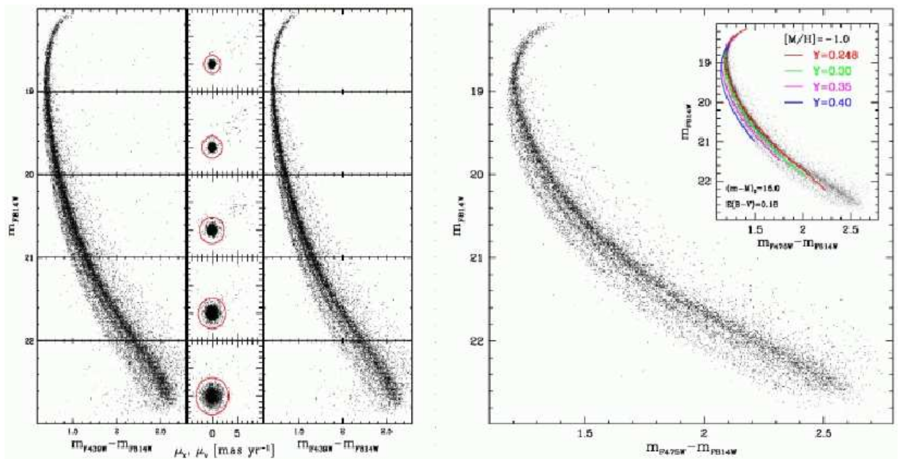

Fig. 4. Left panels: the ACS CMD of NGC 2808 before and after proper motion decontamination, and, in the right panel, the same CMD corrected for differential reddening, clearly showing its triple main sequence[12]. In the insert theoretical sequences with different helium abundances are overplotted.

- ⋆ How did the most massive GCs manage to form/accrete their multiple stellar populations?
- ⋆ Where did the huge amount of helium come from? From 3-8 $M_{\odot}$ AGB stars? Or from where else?
- ⋆ Is ω Cen the remnant core of a tidally disrupted galaxy? And if so, what about the other heavyweight GCs?
- ⋆ Are super-helium populations confined to massive GCs? i.e., can we exclude their presence in massive elliptical galaxies?

3 The Milky Way Bulge and its Globulars

The Galactic bulge harbors a fair fraction of the total populations of GCs, and unlike the metal poor GCs in the halo many of them approach solar metallicity. Observations of two such metal rich GCs taken in the very first Cycle with WFC2 showed that they are as old as Halo GCs, demonstrating that the bulge underwent rapid chemical enrichment and is virtually coeval to the Halo[16]. Fig. 5 shows a comparison between the near-IR CMD of a bulge field obtained with NTT/SOFI, with the CMD of the bulge GC NGC 6528 obtained with HST/NICMOS[17]. The near identity of the two CMDs, and in particular of the luminosity difference between the HB and the MS turnoff, ensure that the bulge as a whole is as old as the cluster, with no trace of an intermediate age population. However, the bulge CMD was cleaned by the disk contamination in a statistical fashion, a procedure that might have also removed a trace young population. A better way of removing the disk

contamination was by picking only HST proper motion bulge members[18], which indeed conclusively demonstrated the virtual absence of an intermediate age population in the bulge. The question then arose as to whether among bulges our own is typical or atypical in this respect.

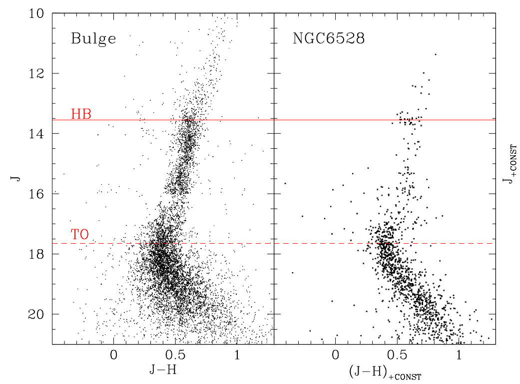

Fig. 5. The near-IR CMD of a bulge field from NTT/SOFI data (left) on the same scale of the HST/NICMOS CMD of the old bulge globular NGC 6528 (right) [17].

4 HST Visits to Andromeda

Next bulge worth checking is that of M31. There had been early claims for the M31 bulge being dominated by an intermediate age population, based on ground based near-IR photometry. This showed an ubiquitous population of very bright red *giants*, then interpreted as intermediate age AGB stars, but there were good reasons to doubt such interpretation, given the extreme crowding of the observed fields. That indeed the apparent bright AGB stars were clumps of fainter RGB stars was beautifully demonstrated by HST/NICMOS imaging[19], as illustrated here in Fig. 6. This study also showed that the near-IR luminosity function of M31 bulge is indistinguishable from that of the Galactic bulge, hence both bulges ought to be equally old.

With the advent of ACS it became affordable trying to reach the old MS turnoff in M31. This was first accomplished on an inner halo field, ~ 11 kpc from the nucleus on the minor axis, investing some 120 HST orbits[20]. Surprisingly, the result was that, besides the old/metal poor population, the field includes also an intermediate age (~ 7 Gyr old), metal rich population making up to 40% of the total. Subsequent HST/ACS projects by the same team probed a disk, a stream, and more outer halo fields in the attempt of mapping the star formation/assembly history of our companion spiral that looks

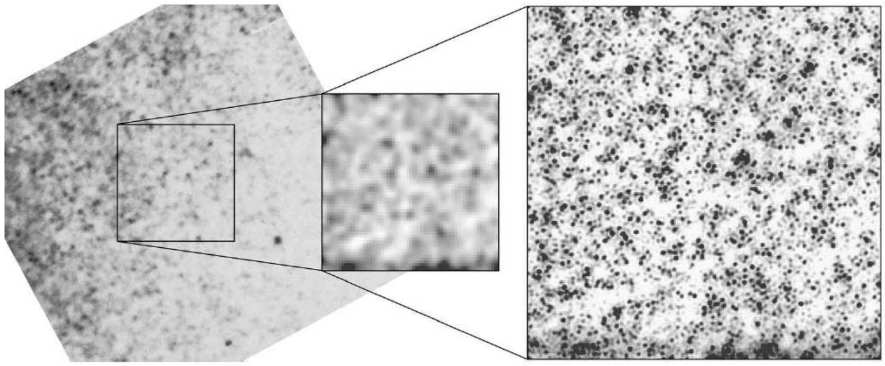

Fig. 6. A ground based K-band image of a field in the M31 bulge, and on the right the same field as seen by HST/NICMOS[19]. What appear as individual bright "stars" on the ground image, are resolved into stochastic clumps of many fainter stars on the HST image.

Fig. 7. A globular cluster in M31 looks so close in this HST/ACS image[21].

so similar, yet turns out to be so different from ours. There is no room left to make justice of these HST results, and to illustrate the power of HST/ACS should suffice to show in Fig. 7 the image of a GC in M31[21].

With the Milky Way and the M31 bulges being dominated by stars at least $\sim$ 10 Gyr old, this is like saying that these bulges had to form the bulk of their stars at $z \gtrsim 1.5$, and evolve passively since then. If so, we should see passive galaxies at such high redshifts in deep spectroscopic surveys, and indeed we do, and once more HST has been instrumental in reveling their *spheroidal* morphology[22][23].

In summary, there has been a very strong and successful use of HST by European astronomers in the field of resolved stellar populations (globular

clusters, MW & M31 bulges and more) as well as on high redshift galaxies. It is also important to stress that the HST+VLT synergy has been very effectively exploited for many programs. Much more is now expected to come in the final years of HST (2008-2014), hopefully with a telescope more powerful than ever (thanks to WFC3/COS/ACS/STIS/NICMOS/FGS).

I would like to thank again Duccio Macchetto, for having invited me to this exciting conference, and for having done so much for HST and for attracting the European astronomers to its scientific use.

References

1. Bedin, L.R., Anderson, J., King, I.R., Piotto, G. 2001, ApJ, 560, L75
2. Villanova, S., Piotto, G., King, I.R., Anderson, J., Bedin, L.R., Gratton, R.G., Cassisi, S., Momany, Y., Bellini, A., Cool, A.M., et al. 2007, ApJ, 663, 296
3. Pancino, E., Ferraro, F.R., Bellazzini, M., Piotto, G., Zoccali, M. 2000, ApJ, 534, L83
4. Bedin, L.R., Piotto, G., Anderson, J., Cassisi, S., King, I.R., Momany, Y., Carraro, G. 2004, ApJ 605, L125
5. Norris, J.E. 2004, ApJ, 612, L25
6. Piotto, G., Villanova, S., Bedin, L.R., Gratton, R. Cassisi, S., Momany, Y., Recio-Blanco, A., Lucatello, S., Anderson, J. et al. 2005, ApJ, 621, 777
7. Sollima, A., Ferraro, F.R., Pancino, E., Bellazzini, M. 2005, MNRAS, 357, 265
8. Sollima, A., Pancino, E., Ferraro, F.R., Bellazzini, M., Straniero, O., Pasquini, L. 2005, ApJ, 634, 332
9. Lee, Y.-W., Joo, S.-J., Han, S.-I., Chung, C., et al. 2005, ApJ, 621, L57
10. Sosin, C., Dorman, B., Djorgovski, S.G., Piotto, G., et al. 1997, ApJ, 480, L35
11. D'Antona, F., & Caloi, V. 2004, ApJ, 611, 871
12. Piotto, G., Bedin, L.R., Anderson, J., King, I.R., Cassisi, S., Milone, A. P., Villanova, S., Pietrinferni, A., Renzini, A. 2007, ApJ, 661, L53
13. Carretta, E., Bragaglia, A., Gratton, R.G., Leone, F., Recio-Blanco, A., Lucatello, S. 2006, A&A, 450, 523
14. Möhler, S., & Sweigart, A.V. 2006, A&A, 455, 943
15. Caloi, V., & D'Antona, F. 2007, A&A, 463, 949
16. Ortolani, S., Renzini, A., Gilmozzi, R., Marconi, G., Barbuy, B., Bica, E., Rich, R.M.1995, Nature, 377, 701
17. Zoccali, M., Renzini, A., Ortolani, S., Greggio, L., Saviane, I., Cassisi, S., Rejkuba, M., Barbuy, B., Rich, R.M., Bica, E. 2003, A&A, 399, 931
18. Kuijken, K., & Rich, R.M. 2002, AJ, 123, 2054
19. Stephens, A.W., Frogel, J.A., DePoy, D.L., Freedman, W., Gallart, C., Jablonka, P., Renzini, A., Rich, R.M., Davies, R. 2003, AJ, 125, 2473
20. Brown, T.M., Ferguson, H.C., Smith, E., Kimble, R.A., Sweigart, A.V., Renzini, A., Rich, R.M., VandenBerg, D.A. 2003, ApJ, 592, L17
21. Brown, T.M., et al. 2004, ApJ 613, L125
22. Cimatti, A., Daddi, E., Renzini, A., Cassata, P., Vanzella, E., Pozzetti, L., Cristiani, S., Fontana, A., Rodighiero, G., et al. 2004, Nature, 430, 184
23. Daddi, E., Renzini, A., Pirzkal, N., Cimatti, A., Malhotra, S., Stiavelli, M., Xu, C., Pasquali, A., Rhoads, J.E., Brusa, M. et al. 2005, ApJ, 626, 680